

## **General Disclaimer**

### **One or more of the Following Statements may affect this Document**

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

National Aeronautics and Space Administration  
Washington, D. C. 20546

March 1983

Smithsonian Institution  
Astrophysical Observatory  
Cambridge, Massachusetts 02138

(NASA-CR-170114) THE STUDY OF THE PHYSICS  
OF COMETARY NUCLEI Semiannual Progress  
Report, 1 Oct. 1982 - 31 Mar. 1983  
(Smithsonian Astrophysical Observatory)  
17 p HC A02/MF A01

N83-22082

Unclas  
03178

CSCD 03B G3/91

The Smithsonian Astrophysical Observatory  
and the Harvard College Observatory  
are members of the  
Center for Astrophysics

The NASA Technical Officer for this Grant is Dr. Robert A. Fieseler  
Code 2-1, Headquarters NASA, Washington, D. C. 20546

THE STUDY OF THE PHYSICS OF COMETARY NUCLEI

Grant NSG-7082

Semiannual Progress Report No. 17

1 October 1982 through March 31, 1983

Principal Investigator

Dr. Fred L. Whipple

Prepared for  
National Aeronautics and Space Administration  
Washington, D. C. 20546

March 1983

Smithsonian Institution  
Astrophysical Observatory  
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory  
and the Harvard College Observatory  
are members of the  
Center for Astrophysics

The NASA Technical Officer for this Grant is Mr. Joseph M. Boyce,  
Code EL-4 , Headquarters NASA, Washington, D.C. 20546

### Cometary "Geology"

The continuing research of this project has shown that the observations of comets provide at least five indicators of non-uniform activity over their icy-conglomerate nuclei (i.e. spottedness):

- a) Periodic "parabolic" envelopes
- b) Irregular motion of activity centers over the nucleus
- c) Periodicity of halo diameters leading to determinations of rotation periods
- d) Unusual light curves indicating latitudinal variations in activity
- e) Jets, rays, fans, streamers etc. of the inner coma

The extremely narrow dust jets seen near the nuclei of some brighter comets cannot be explained by the assumption of small isolated dust sources acting independently of surrounding areas on the nucleus. The dust would be carried out by the expanding sublimating gas in broad fans or halos (as are frequently observed) if the gas motion were not constrained and channeled by simultaneous gas sublimation in large areas surrounding the dust sources. For the periodic Comet Swift-Tuttle, 1862 III (the source of the Perseid meteor shower), Z. Sekanina (Ast. Journ., 86, 1741, 1981) has isolated eight small sources of very fine dust, of micron and submicron dimensions, on the nucleus. I find several lines of evidence to indicate that these small areas of fine-dust production are, in fact, less active in terms of momentum transfer than the surrounding "gassy" regions. Furthermore I find other evidence that the same is true of very dusty comets compared to other comets.

These results combine to suggest that during some period of their evolution many comets accumulated substantial layers of very fine dust combined with ice that either was less volatile than the average or else was "overloaded" with a high abundance of dust. On subsequent comet growth

by encounters these dusty volumes were distributed erratically in the final comet nuclei. If, indeed, the dusty ices are less volatile than the average, the dusty sources may occur as relatively colossal outcroppings on many comet nuclei. Under the very low gravities involved, their bizarre formations may occasionally crumble to provide the sporadic fine-dust phenomena seen near the nuclei of many bright comets.

A paper on this subject "Cometary Nucleus and Active Regions" was presented at the International Conference on Cometary Exploration held in Budapest, Hungary, in November 1982, and is included as an appendix to this report. Research on the nature of this dusty activity is being continued particularly with regard to the observed nuclear magnitudes of comets.

#### The Wasting of Cometary Nuclei

The research on the simulated life histories of rotating comets continues but has not yet been published because the calculated simulations have led to a discrepancy with observation, viz. the poles of more developed comets are calculated to become more and more perpendicular to their orbital planes whereas a number of actual poles of older comets lie rather close to their orbital planes. The reason for the discrepancy became apparent from the concurrent studies (above) of active regions on cometary nuclei. The development of less active regions on a polar hemisphere of a cometary nucleus can change the polar precession direction as compared to that for a symmetrical nucleus as assumed in the calculations. This concept will be exploited in new calculations to be carried out as time permits. Of particular interest is the cause of polar reductions in activity: intrinsic or by blanketing?

#### Halley's Comet

A considerable computing effort was made in the search for evidence that the observed astrometric positions of comets

may be systematically in error because they measure the center of light of the nuclear region in the coma rather than the true dynamical position itself. Rotation of the nucleus might cause variations in this effect. Positional residuals for Halley's Comet in 1909-1910 were kindly provided by D. Yeomans of the Jet Propulsion Laboratory. A computer program was set up to compare two intervals of observations in a search for similar periodic variations in the residuals of each set, both in right ascension and in declination. A fine mesh of nuclear rotation periods was taken over a range of near 10.1 and near 20.2 hours. Essentially a power spectrum was obtained.

No evidence for any of the periods could be found. This negative result might result from an erroneous choice of period ranges, from too much "noise" in the residuals or from the lack of a significant effect. If the amplitude of the effect is, as likely, only a small fraction of an arc second, it probably is too small to be found in sets of only some 60 residuals, with a standard deviation exceeding 2 arcseconds for a single observation.

Conclusion: the period ranges may be in error or the effect rather small.

Activities with regard to Halley's Comet continue. Whipple acts as a member of the steering group of the International Halley Watch, as a consultant to the imaging team of the European Space Agency Giotto Halley Mission, and continues studies of the observations of Halley's Comet in the 1835 and 1910 apparitions. The current effort centers on the meaning of nuclear magnitude determinations for Halley's Comet and for a number of other comets.

#### Other Activities

Continued use is made of old and new cometary literature to determine spin periods of comets or to improve older deter-

minations, and to improve the theory of the nature of cometary nuclei. A major effort centers on the above mentioned interpretation of nuclear magnitudes generally.

Publications and Presentations by F. L. Whipple

"Comets: Nature, Evolution and Decay"

Published as CFA Preprint No. 1721

and in Press: International Astronomical Union Reports of  
the XVIIIth General Assembly

Paper presented at the American Astronomical Society, January 1983

"Cometary Nucleus in Active Regions"

Published as CFA Preprint No. 1763 and in Press: The Central  
Research Institute for Physics Conference Proceedings of the Inter-  
national Conference on Cometary Exploration

Paper presented at the International Conference on Cometary Ex-  
ploration at Budapest, Hungary, November 1982 and at the Planetary  
Geology Principal Investigators meeting, January 1983.

**ORIGINAL PAGE IS  
OF POOR QUALITY**



**APPENDIX I**

# CENTER FOR ASTROPHYSICS

## PREPRINT SERIES

---

No. 1763

COMETARY NUCLEUS AND ACTIVE REGIONS

Fred L. Whipple

Harvard-Smithsonian Center for Astrophysics

Submitted to

The Central Research Institute for Physics  
Conference Proceedings  
of the  
International Conference on Cometary Exploration

Presented at

Budapest, Hungary

November 1982

**Center for Astrophysics**

60 Garden St.

Cambridge, Massachusetts 02138

# COMETARY NUCLEUS AND ACTIVE REGIONS

Fred L. Whipple

Smithsonian Astrophysical Observatory  
Cambridge, Massachusetts 02138

## ABSTRACT

On the basis of the icy conglomerate model of cometary nuclei various observations demonstrate the "spotted" nature of many or most nuclei, i.e., regions of unusual activity, either high or low. Rotation periods, spin axes and even procession of the axes have been determined. Narrow dust jets near the nuclei of some bright comets require that small sources be embedded in larger active areas. Certain evidence suggests that very dusty areas and very dusty comets may be less active, respectively, than surrounding areas or other comets.

## INTRODUCTION

The concept that comet activity arises from solar heat sublimating an icy conglomerate nucleus (Whipple, 1950, 1951, 1955) is now generally accepted as consistent with the observed phenomena of comets. The concept is also consistent with an origin in the outer regions of the proto-solar system or in associated gas and dust clouds where temperatures were low enough to permit the existence of  $H_2O$  ice and other ices, along with less volatile earthy materials. Accumulation into bodies up to tens of kilometers in size then occurred. Indeed, comets or cometesimals appear as the likely building blocks of Uranus and Neptune in the manner that asteroidal-type bodies of more refractory material were the building blocks of the terrestrial planets.

This simple overall picture of the nature of comets and their role in solar system formation raises a host of tantalizing questions that must be answered if we are to understand many of the basic circumstances and processes that brought the Earth and

# COMETARY NUCLEUS AND ACTIVE REGIONS

Fred L. Whipple

Smithsonian Astrophysical Observatory  
Cambridge, Massachusetts 02138

solar system into being. The present paper will deal primarily with nonuniformities in the nature and properties of the cometary nucleus, with limited reference to vital questions of origin, orbital changes, Oort-cloud characteristics and chemistry. The reader is referred to Donn and Rahe (1982) for a review of current information about the physical structure and related thinking concerning the nucleus.

The basic data that led to the icy conglomerate model of comets were (a) associated meteor streams, (b) rapid dispersion of particles in meteor streams, (c) the large quantities of gases lost in each perihelion passage, (d) the long lifetimes of some periodic comets (particularly P/Encke), and (e) the established lack of sources of replenishment of gases by absorption on small particles in circumsolar space. These data demanded a finite enduring reservoir of gas and dust, clearly an icy reservoir for each comet. The added fact of nongravitational (NG) motion for some comets then made possible a semiquantitative theory. If rotating icy nuclei produce cometary phenomena: sublimation, then one should expect a time lag from sunrise to initiation of sublimation and a maximum mass loss in the cometary afternoon. The outgoing gases must react with the nucleus by conservation of momentum to produce a force, which because of the time lag could change the angular momentum in the orbit about the Sun, an increase or decrease in period depending upon the sense of the rotation.

Marsden (1982) lists values of NG accelerations for the orbit of 35 periodic comets. The transverse  $A_2$  term (minus for decreasing and positive for increasing periods) is minus in 17 cases, plus in 13 cases and changes sign in 5 cases. We may conclude first that the sense of rotation is essentially random with respect to the orbital motion for the periodic comets. On the other hand, systematic changes in  $A_2$  occur for a few comets (particularly P/Encke, P/Faye and P/Brooks 2) and real changes in sign over a dozen or so revolutions in one or two cases. We shall consider these anomalies later.

The observed loss rates for gases coupled with reasonable latent heats of vaporization, moderate afternoon lag angles of several degrees and the observed NG accelerations then place the dimensions of the periodic comets in the kilometer range for mean densities the order of  $1 \text{ g cm}^{-3}$ . Combined evidence from spectroscopy, light curves

and other cometary data and theory suggest that  $\text{H}_2\text{O}$  ice is the major volatile for the older short-period comets (Kresak, 1973; Delisemme, 1982; Wyckoff, 1982) although frequent examples of great activity at large solar distances make it clear that far more volatile ices are present in many comets particularly newcomers from the Oort cloud. The refractory dust component appears to contribute somewhat less than half of the mass of comets, as would be expected if comets represent the fraction of the solar mix of elements that could freeze out or remain as solids at temperatures of the order of 50K.

The observational evidence for variations in activity over the surfaces of cometary nuclei includes at least five different effects:

- Periodic "parabolic" envelopes in the coma (C/Donati, for example);
- Activity centers that move on P/Schwassmann-Wachmann 1, observed as asymmetric comas;
- Periodicity in halo diameters of the coma in many comets;
- Unusual light curves (P/Encke, for example);
- Jets, rays, fans, streams, etc., of the inner coma, sometimes associated with effects in both the dust and ion tails.

#### ACTIVE REGIONS ON COMETARY NUCLEI FROM COMA MEASURES

The postulated lag angles in sublimation should lead theoretically to observable asymmetrical comas when the geometry Sun-comet-Earth is appropriate. Sekanina (1979) exploited measured coma asymmetries to determine the directions of the spin axes and the lag angles for the nuclei of four short-period comets. He assumed that the primary sublimation occurs on the small latitude circle of the nucleus that includes the subsolar point, an assumption of uniformity in the structure of the nucleus. He found lag angles of a few degrees up to nearly  $90^\circ$  and spin orientations consistent with the observed NG forces.

At the same time Whipple (1977, 1980), in studying P/Schwassmann-Wachmann (P/SW1), determined the spin axis but found that the activity was spotted, was not confined to the subsolar region and that the lag angle measured from the solar meridian was highly variable, often negative. Even more surprising, the same small area on the nucleus would often be active at intervals of integral multiples of 5.6 days.

and greater transverse NG forces for more rapidly rotating nuclei. Thus the statistics roughly support the values in Fig. 1. For P/Halley my determination of  $10.3$  for the spin period is probably nearly correct. Double the period seems slow for a bright comet with a sizeable NG acceleration.

The assiduous observations of many observers over nearly a century and a half have made the results of Fig. 1 possible. The two major contributors were Max Beyer and George van Biesbroeck while J. F. Julius Schmidt made extraordinarily consistent measure of coma diameters for several comets. Because of this ability, he was the first to recognize and determine the rapid repetition rate of the C/Donati halos (Schmidt, 1863).

The observations of coma diameter for several of the comets were too infrequent or badly spaced in time for reliable period determinations. Several may have had very short periods not resolvable from the data. The spin axes of others may have been oriented unfavorably. In addition, multiple active areas certainly confused the situation for a few comets. Hence, we can conclude that among the well observed comets of all orbital types, at least one-fourth and probably more than one-half possess areas on their nuclei that are much more active in sublimation than the remaining surface.

One strong correlation shown among the spin periods of Fig. 1 is an increase in the period (at the 2.4 sigma level) with increasing intrinsic brightness of the comet, presumably with dimension. This correlation may well represent some process in the mode of origin.

The active areas do not repeat at all solar meridian passages; their level of activity is quite variable. Occasionally, they tend to drift in position on the nucleus with time, particularly for a slowly rotating nucleus such as that of P/SW1. Even polar active areas near the subsolar point act erratically. There is clearly a mechanism that stops the activity but then recovers to allow subsequent sublimation - a subsurface warming process that precedes and limits the activity? On P/SW1, the fallback of larger meteoroids to crack the surface may play a role in expanding an initial activity. Such a mechanism, however, operates best on large nuclei, otherwise it might mainly cause blanketing (see, e.g. Brin and Mendis, 1979).

The zero date (Z-D) of the initiation of such activity was determined by measuring diameter of the halo (or coma) reduced to km and divided by the expansion velocity  $v = 535 \text{ m s}^{-1}$  (observed by Bobrovnikov, 1954) where  $r$  is the solar distance in AU. This halo method led to a rotation period of  $5.0$  for P/SW1 and  $4.6$  for Comet Donati, 1858 VI, for which the halos were extraordinarily conspicuous (Whipple, 1978). In a search for coma diameter observations from more than 70 comets, Whipple (1982) found adequate data and some evidence of periodicity in 47 cases. About half of these appeared to give reliable periods. Figure 1 presents the normalized log (period) distribution for the 47 comets compared to that for 41 asteroids of diameter  $\leq 40 \text{ km}$  from the compilation by Harris and Burns (1979).

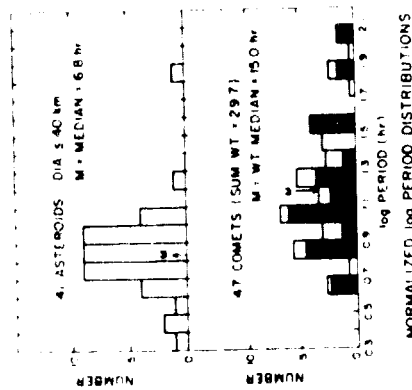


Fig. 1. Log-period distribution for comets and small asteroids. The black bars represent the high-weight determinations.

There is yet little external evidence to substantiate the accuracy of these spin periods. Eight periodic comets have transverse NG acceleration determinations ( $A_2$ ) in Maraden's list (1982). The logarithmic mean of their spin periods is  $5.3$  compared to  $20^h$  for four others for which NG accelerations have not been determined, excluding the very slow rotators, P/SW1 and P/SW1-Tuttle. We should expect larger lag angles

# RESULTS FROM JETS RAYS AND FANS

The most obvious evidence for active areas on cometary nuclei are the jets, rays, fans and other irregularities around and close to the nuclei of bright comets, usually seen visually under high resolving power (Fig. 3). Quantitative interpretation of these phenomena has been slow in developing because of their complicated structure, rapid variations, the lack of continuous uniform surveillance and the absence of a basic model for the nucleus. For P/Swift-Tuttle, Schmidt (1863) measured a period by two types of oscillation in the tail ( $P = 68h$ ), periodic reappearances (Wiechert) of configurations very near the nucleus (72h), and the position angles of the fans (Sommerfeldacher). This last method led to a period of 65h, in remarkable agreement with Sekanina's (1981) value of  $66^{h}5$ .



Fig. 3. Winnecke drawing of P/Swift-Tuttle, August 23, 1862.

Horn (1908, later Horn d'Arbut) apparently was the first both to visualize the nucleus of a comet as a discrete rotating entity and also to attempt to determine its spin period and axis of rotation. From 59 photographs of C/Daniel, 1907 IV, he found that the symmetry axis of the nuclear oval oscillate 73 times about the tail axis to give  $P = 16^h$ . His complicated geometrical analysis led him to calculate the direction

## The Unusual Light Curve of P/Encke

Comet P/Encke displays a rare light curve for a short-period comet. The brightness increases rapidly before perihelion whereupon it fades even more rapidly. Whipple and Sekanina (1979) conclude that this peculiar behavior arises from one polar region that is much less active than the other (Fig. 2). The variation in activity with latitude over the nucleus is an essential factor in explaining the detailed secular variation of the NG acceleration of the comet. The latitude dependence of activity may be intrinsic to the comet structure but we prefer the explanation that the inactive pole was covered with meteoroidal debris during a long interval before 1700 AD when the inactive pole was oriented away from the Sun near perihelion. The nuclei of many comets may well be partially blanketed in this fashion.

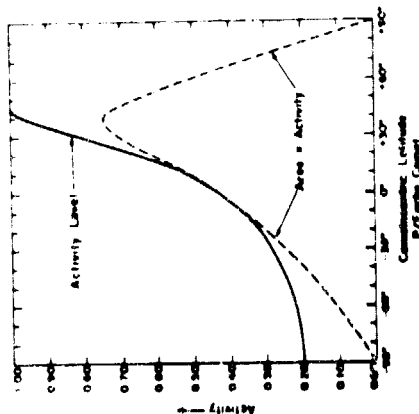


Fig. 2. Activity level as a function of latitude on the nucleus of P/Encke. Dashed line: activity  $\times \cos$  (latitude).

It appears to the author that such fallback material constitutes the major if not the only 1/2 to 1/3 of unblancketed meteoroidal material on comets. Generally such material is associated with the fans.

of the spin axis. Vorontsov-Velyaminov (1930) also concluded that for C/Brooks, 1893 IV, "the movement of the tail and its form can be explained when it is interpreted like a beam continuously emitted by the block which rotates round the radius-vector with the period of 100d." Unfortunately these concepts were not quickly adopted by astronomers. Later Dubiago (1948) suggested that nongravitational changes in the orbital periods of comets might arise by the tangential ejection of dust from discrete nuclei, but he did not specify the physical process.

The difficulty of interpreting the near nuclear phenomena is illustrated by the fact that Bobronikov's (1931) massive compilation of the 1910 P/Halley observations has lain fallow for half a century without competent analytic treatment. Sekanina's (1981) brilliant study of P/Swift Tuttle, 1862 III, (P/ST) at last gives us a clear picture of the processes over the surface of the nucleus that produce jets, envelopes and tail bands. A short review of this basic paper cannot do adequate justice to it. The paper must be read to be fully understood and appreciated.

Sekanina finds highly organized motions of dust flow in sharp narrow jets. The "jets were products of brief bursts of dust from the eight discrete emission areas" illustrated in Fig. 4. The basic data were derived primarily from published drawings and measurements by A. Winnecke (Fig. 3) and from unpublished observational records and drawings made by G. P. Bond, utilizing the "Great" refractors (38-cm apertures) of Pulkova and Harard, respectively. Among these data, including micrometric measurements of the jet and detailed descriptions of asymmetrical envelopes in the coma and tail combined with numerous data by several European observers, Sekanina has utilized 261 measures of jet orientation and 173 data on jet length. He has been able to follow the development of 72 jets. For many of them he has determined not only the time of initiation, position on the nucleus and duration, but also has followed the subsequent motions of the particles as affected by solar radiation pressure. On the drawings by Winnecke and Bond he superposes grids of velocity and  $\beta$  (radiation pressure/solar gravity) as projected onto the sky (Fig. 5). In this manner he shows that these phenomena are specifically dust ejections occurring normal to the surface of the nucleus from localized small areas.

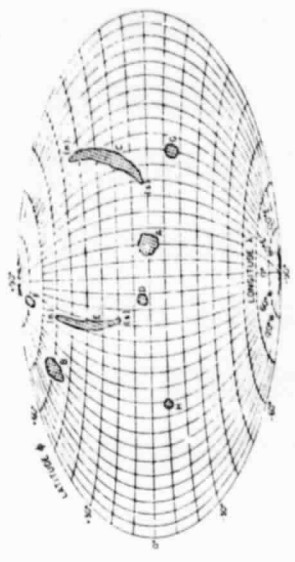


Fig. 4. Sekanina's drawing of active fine-dust areas on P/ST.

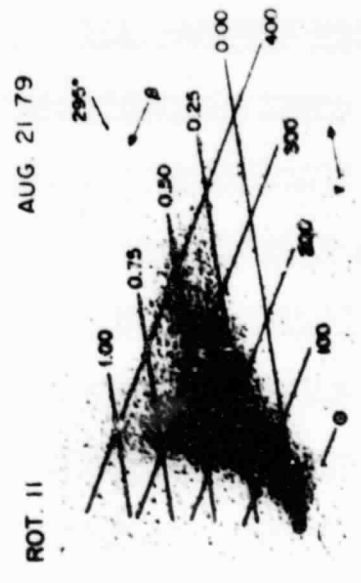


Fig. 5. Grid of  $v$  and  $\beta$  superposed on Fig. 5 by Sekanina (1981).

He locates the positions of eight dusty active areas on the nucleus with considerable precision, deriving a consistent spin period of 66.5 and a specific polar axis having an obliquity of  $80^\circ$  with respect to the orbit plane (prograde rotation). Area B was active for 20 rotations from August 24, to September 15, 1963, areas A and Cn for about a dozen rotations and the six other active areas for lesser intervals.

The following numerical results derived or calculated by Sekanina will be discussed in the next section of this paper by way of further interpretation of the surface phenomena involved:

- A. The total area of the nucleus covered by the active regions was at most 1% with typical jet widths of  $\sim 10^\circ$  as measured from the center of the nucleus.
- B. The escape of gas observed in the active areas to carry the observed dust requires a gas production rate of some  $3 \text{ to } 8 \times 10^{-6} \text{ g cm}^{-2} \text{ s}^{-1}$ , where the loading factor, or dust/gas mass ratio, is taken to be 0.3.
- C. The "mass of dust per ejection is calculated to be in the general range between  $2 \times 10^8$  and  $2 \times 10^9 \text{ g}$ ."
- D. No active areas appear over a longitude range of  $140^\circ$  in the nucleus.

#### Further Interpretation of Dust Emissions

First note the narrow structure of the jets (A above and Fig. 3), the order of  $10^\circ$  or less. If these areas were the major source of sublimation on the nucleus the jets could not maintain their radial character at distances of hundreds of nuclear radii as observed. The gas would spread out in fans covering large solid angles and would produce halo-type structures as seen in various comets. The micron and submicron particles would follow the gas flow up to and beyond the distance that gas is thermalized by collisions, the order of 20 radii from the nucleus for  $\sim 2000$ s (Probst, 1968; Finsen and Probst, 1968). With strong sublimation from surrounding large areas on the nucleus, however, the dust from the small sources within these areas would move essentially radially, following the total gas flow. A dust particle of mass  $m_d$  would be thermalized to a mean velocity, which roughly is equal to the thermal velocity of the gas (of mass  $m_g$ ) reduced by factor of  $(m_g/m_d)^{1/2}$ , the order of  $1/1000$  for a grain of radius  $0.5 \mu\text{m}$ . This corresponds to the jet spreading in the gas motion by  $\sim 2/1000$  radians, an insignificant angle. Thus the observation of narrow jets requires that the active dust areas be immersed in much larger areas of active sublimation.

This conclusion is supported by Sekanina's required production rate (B above) to eject the dust. Comet P/ST is a relatively bright comet, of intermediate age in the Oort sense, much in the class of P/Halley and C/Bennett, 1970 II, with regard to both

Initiation of emission usually occurred in the afternoon but areas Cs, Cn, B and G showed a few morning starts. The length of the jets before radiation pressure turned the particles away from the solar direction and curved the jets, spreading out the particles, indicates relatively short emission intervals of one to a few hours, typically  $0.1$  to  $0.5$  days, with emission often ending while the solar radiation was still strong. A new jet is straight and sharp to  $0.25$  to  $0.75$ , until the radiation pressure takes precedence over the radial ejection velocity. For a jet properly oriented in projection, the later stages of diffuse curvature and spreading are diagnostic of  $\beta$ . The grids broadly limit the ejections to the range from  $v = 200 \text{ ms}^{-1}$  with  $\beta = 0$  to  $v = 400 \text{ ms}^{-1}$  with  $\beta \approx 0.5$ , although "the presence of particles with  $\beta > 0.5$  is strongly suggested in late rotations for area E and in some cases for area A." He finds that an S-shaped figure for a jet is an unambiguous dielectric signature for the dust with maximum  $\beta = 0.5$  whereas a saber-shaped figure (Fig. 5, 6) indicates absorbing dust in addition. Particles smaller than  $0.1 \mu\text{m}$  in radius appear to be largely absent. In one case a splitting of the jet clearly indicates the presence of both dielectric and absorbing particles.

Wincke's drawing of P/ST on August 21, 1862.

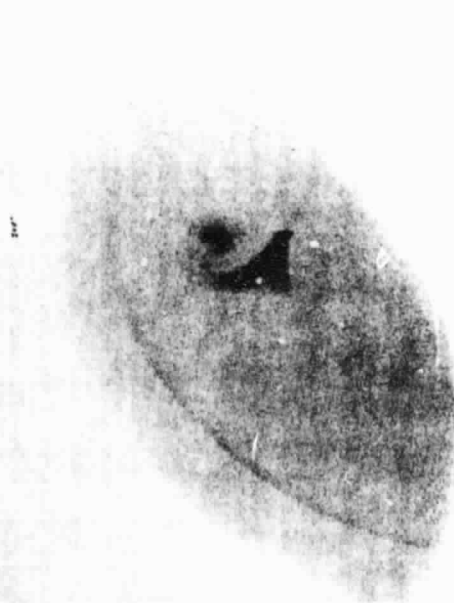


Fig. 6. Wincke's drawing of P/ST on August 21, 1862.



of  $2 \times 10^8$  to  $2 \times 10^9$  g s<sup>-1</sup> per jet applies only to an area of diameter  $\sim 13^\circ$ , the jet lasting about 0.1. The revised dust production rate then becomes  $5$  to  $50 \times 10^{-6}$  g cm<sup>-2</sup> s<sup>-1</sup>, to be compared to the estimated rate for such a comet at the subsolar point,  $94$  to  $200 \times 10^{-6}$  g cm<sup>-2</sup> s<sup>-1</sup>. By either calculation the production rate of the fine dust appears to be small compared to the expected gas production rate.

Much of this evidence to show that the active dust areas on P/ST are immersed in far larger areas of activity also indicates that the dust areas are less active than the surface regions around them. From the lack of observed Type II or Type III tails, P/ST can be classified as a comet of low dust/gas ratio, although the ratios of 1/125 to 1/2 must certainly underestimate the total fraction of earthy material. More relevant as additional evidence is the variation of dust activity with zenith distance of the areas at noon ( $Z_n$ ), which Sekanina finds to vary as  $(\cos Z_n)^{2.4}$  for area B, much more rapidly than the insolation. Area A died out as  $Z_n$  increased from  $53^\circ$  to  $64^\circ$  although its activity nearly matched Bobrovnikov's curve of the total brightness of the comet. Area A, however, anticipated the light curve by about a week, dropping somewhat more rapidly after perihelion.

These signs for lower than average activity in dusty regions suggests the possibility that in general dusty comets may be less active than comparable comets that are less dusty. If we look to Donn's (1977) tabulation of comets with high (H), medium (M) and low (L) dust/gas ratios we find 10 periodic and 6 very long-period comets in common with Marsden's (1982) compilation of comets having measurable NG accelerations. The comparison leads to the following results:

Comets	No.	Dust/Gas	Mean Acceleration
Periodic	4	H	$A_2 = 0.016$
Periodic	6	M and L	$A_2 = 0.057$
Long Period	3	H	$A_1 = +1.5$
Long Period	3	M and L	$A_1 = +3.8$

Here  $A_2$  is the maximum absolute value of the transverse acceleration for each comet and  $A_1$  is the radial component, both in Marsden's "style II" system. The comets of medium and low dust/gas ratios tend to show comparable NG accelerations, systematically larger than those comets with high dust content, supporting the conclusion that dusty comets are less active than the others.

activity and absolute brightness. Vekhovitskii (1964) rates P/ST with  $H_{10} = 4.0$  and P/Halley 4.6. C/Bennett is comparable in absolute brightness. Delsemme (1977) summarizes the  $H_2O$  production measures for C/Bennett, reduced to  $r = 1$  AU, as  $\sim 60 \times 10^{28}$  g s<sup>-1</sup> or  $18 \times 10^6$  g s<sup>-1</sup>. Although the radius of no comet is well determined, various pieces of evidence suggest that the radii of these comets are in the order of 3.5 km. If, for simplicity, we accept this radius and an average sublimation over  $\pi/2$  ster at the subsolar point at  $r = 1$  AU for P/ST, the production rate of  $H_2O$  molecules alone becomes  $\sim 94 \times 10^6$  g cm<sup>-2</sup> s<sup>-1</sup> averaged over this area. For  $H_2O$  plus clathrates Whipple and Huebner (1976) calculate that the total production rate at the subsolar point at  $r = 1$  AU is  $\sim 200 \times 10^6$  g cm<sup>-2</sup> s<sup>-1</sup> for a low albedo. These values are more than an order of magnitude larger than Sekanina's required 3 to  $8 \times 10^6$  g cm<sup>-2</sup> s<sup>-1</sup> (B above) for fine dust ejection over the active dust areas.

Furthermore a much higher production rate for P/ST than required for fine dust is demanded by the existence of the associated P/ST meteor stream and the forward tail observed in 1982. Perseid meteoroids certainly occur in the 0.1 g mass range or larger, corresponding to radii of thousands of  $\mu$ m, and require for ejection larger production rates than  $8 \times 10^6$  g cm<sup>-2</sup> s<sup>-1</sup> (see e.g., Whipple and Huebner, 1976, Eq. 4).

Some direct evidence for large active areas stems from my calculations for P/ST. From 13 coma-diameter measures by Schmidt (1863), August 13-31, 1865, I derived a reasonably well determined period of 32<sup>h</sup>, almost exactly half of Sekanina's (or Schmidt's) value. It appears that two major areas were active, separated by nearly  $180^\circ$  in longitude on the nucleus. The areas appear to coincide roughly with Sekanina's areas B and Cn (about  $190^\circ$  apart) but the agreement is not precise.

#### The Activity Level of Dust Areas and of Dusty Comets

Note that Sekanina's estimate of the fine-dust production rate is the order of  $2 \times 10^8$  to  $2 \times 10^9$  g per burst (C above) with an average of four bursts in 66<sup>h</sup> 5 (D above), leading to an average rate of  $3.3$  to  $33$  to  $330 \times 10^3$  g s<sup>-1</sup>. Spreading this rate over 1% (A above) of the area of a 3.5-km-radius nucleus then makes the average production rate of fine dust some  $0.2$  to  $2 \times 10^6$  g cm<sup>-2</sup> s<sup>-1</sup> or higher if the actual area covered is less than 1%. The expected average total production rate of  $H_2O$  is  $12$  to  $25 \times 10^6$  g cm<sup>-2</sup> s<sup>-1</sup>, i.e., 6 to 125 times greater. Sekanina informs me, however, that the estimate

A further test of the hypothesis can be made from Kresak's (1973) compilation of the maximum solar distance,  $r_0$  to which faint 13th magnitude (average) comets had been observed. Using Donn's classification dust/gas, we find six H comets (omitting the much brighter P/Kearna-Kwee) with  $r_0 = 2.32$  AU and seven L and M comets with  $r_0 = 2.58$  AU. Thus dusty comets appear to fade out somewhat more rapidly with solar distance than other comets.

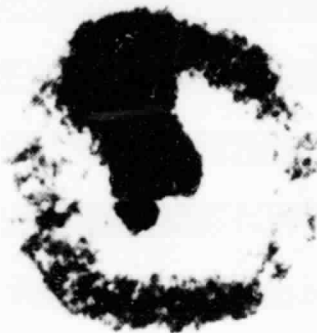
#### SUMMARY OF EVIDENCE CONCERNING FINE-DUST EJECTION AND FINAL COMMENTS

- 1) The narrowness of many jets for P/ST requires both that the dust emission areas be small and that they be imbedded in larger areas of equal or greater activity. Occasional wide fans and halos demonstrate the phenomena when the latter condition is not satisfied.
- 2) Sekanina's gas production rate derived from the jets to raise the fine dust is much less than the average expected for a comet in P/ST's brightness class, suggesting that the average production rate around the dust sources is greater than that within the sources.
- 3) The dust production rate calculated by Sekanina from the dust sources is smaller than expected from areas of average dust/gas ratios for other similar comets. This may imply an overload of dust to ices in the dusty zones.
- 4) The gas production rate in 2) above appears inadequate to raise the larger Perseid meteoroids.
- 5) The variation of activity of the dust sources with zenith distance of the noon-day Sun, as  $(\cos)^{2.4}$ , is larger than expected for ordinary active areas on comets.
- 6) Dusty comets show smaller NG accelerations than less dusty comets of comparable intrinsic brightness.
- 7) Dusty comets tend to fade more rapidly at great solar distances than less dusty comets.

The general behavior of the micron dust jet emissions as described above suggests that they arise from localized regions of somewhat less volatile materials than broader active regions around them. If this is true I visualize them as resembling exposed

geological dikes, tilted strata exposed above the surrounding areas. Sublimation of nonuniform materials would produce grotesque formations with overhanging ledges, mushroom tops and extremely slender towers. The irregular wasting of such features would expose fresh surfaces for sublimation on successive comet days.

The collapse of large features might well be the source of the two unusual outbursts of P/ST on August 18/19. They were observed as a rare, nearly circular halo drawn by Bond (Fig. 7), an inner smaller halo, and a secondary condensation. The smaller halo coincides fairly well in time with the first strong stellar nucleus observed by Bond while the large halo initiation may precede Sekanina's 10th rotation of area B, by a few hours. The position of the outbursts remain uncertain but their character is quite different from the other phenomena of the comet. Both suggest outbursts from extremely localized regions, material expanding radially, not from the center of the nucleus but from the surface - in other words, bursts of material not channelled by the surrounding gases from surrounding sublimating areas. Note that the major part of the activity need not arise from the tiny but intense source area. A heavy localized outburst could eject large pieces about its neighborhood initiating activity by breaking up the crust.



AUG 19 19

Fig. 7. Bond drawing of P/ST on August 19, 1962.

- Sekanina utilizes three measurements of the condensation to determine an acceleration from zero velocity to motion radially from the Sun at  $\beta \sim 1.25$ . The calculation is consistent with a source at area B. He tentatively identifies the condensation as a "large tenuously banded fragment (or fragments) disintegrating into mostly submicron-sized pieces."
- Sekanina's discovery that several of the active dust regions define a crude small circle on the nucleus suggests their formation as a layer on a small comet that encountered the main nucleus at a very low velocity. The remainder of the small comet could have sublimed away leaving only the nearly circular and irregular dike-like formation.
- The totality of this evidence suggests that during the formation of comets there was a considerable period of time over a considerable region of space during which micron-sized dust accreted in relatively thick layers on many comets of all sizes. The thickness of the layers was the order of at least tens of meters, the dust being accumulated along with ices of only moderate volatility. The expected volatility depends directly upon the unknown loading factor of the dust/gas ratio, which may be high.
- The author is indebted to the National Aeronautics and Space Administration's Division of Planetary Geology for support of this research and to the Smithsonian Institution for travel support to the Budapest conference. Discussions with Zdrnek Sekanina have been extremely valuable.
- Addendum: For P/Halley mission planning it may be of interest that I find the spin pole tentatively at Right Ascension  $225^\circ \pm 25^\circ$ , and Declination  $-70^\circ \pm 10^\circ$  (Eq. 1950.0) giving an orbital obliquity of  $40^\circ \pm 10^\circ$  and prograde motion with respect to the orbit.
- REFERENCES
- Bobrovnikov, N. T. 1931. Pub. Lick Obs. 17, Part II, p. 310.  
 Bobrovnikov, N. T. 1954. Astron. Journ. 59, 357.  
 Brin, G. D., and Mendis, D. A. 1979. Astrophys. Journ. 229, 402.  
 Delsemme, A. H. 1977. In Comets Asteroids Meteorites, ed. by A. H. Delsemme, pp. 3-13. Univ. of Toledo Press.  
 Delsemme, A. H. 1982. In Comets, ed. by L. Wilkening, pp. 95-130. Univ. of Arizona Press.  
 Donn, B. 1977. In Comets Asteroids Meteorites, ed. by A. H. Delsemme, pp. 15-23. Univ. of Toledo Press.  
 Donn, B., and Rahe, J. 1982. In Comets, ed. by L. Wilkening, pp. 203-226. Univ. of Arizona Press.  
 Dubiago, A. D. 1946. Astron. Journ. USSR, 25, 361.  
 Finson, M. L., and Probst, R. F. 1968. Astrophys. Journ. 154, 327.  
 Harris, A. W., and Burns, J. A. 1979. Icarus 40, 115.  
 Horn, G. 1908. Mem. Soc. d. Spettroscopisti, Italy 37, 65.  
 Kresák, L. 1973. Bull. Astron. Inst. Czech. 24, 264-283.  
 Marsden, B. G. 1962. Catalogue of Cometary Orbits, 4th ed. Minor Planet Center, Smithsonian Astrophys. Obs., Cambridge, Mass.  
 Probst, R. F. 1968. Collection Dedicated to the Sixtieth Birthday of Academician L. I. Sedov, ed. by M. A. Lavrent'ev. Izdatel'stvo Akad. Nauk. S. SSR (Moscow).  
 Schmidt, J.-F. J. 1863. Publ. Athens Obs., Ser. I, 1, 1.  
 Sekanina, Z. 1979. Icarus 37, 420.  
 Sekanina, Z. 1981. Astron. Journ. 86, 1741.  
 Velskyvatski, S. K. 1964. Physical Characteristics of Comets, English Translation, NASA TTF-80, 596 pp.  
 Vorontsev-Velyaminov, B. 1930. Russian Astron. Journ. 7, 90.  
 Whipple, F. L. 1950. Astron. Journ. 111, 375; 1951, Ibid. 113, 464; 1955, Ibid. 121, 750.  
 Whipple, F. L. 1977. Bull. Amer. Astron. Soc. 9, 563.  
 Whipple, F. L. 1978. Nature 273, 134.  
 Whipple, F. L. 1980. Astron. Journ. 85, 305.  
 Whipple, F. L. 1982. In Comets, ed. by L. Wilkening, pp. 227-250. Univ. of Arizona Press.  
 Whipple, F. L., and Huebner, W. F. 1976. Ann. Rev. Astron. Astrophys. 14, 143.  
 Whipple, F. L., and Sekanina, Z. 1979. Astron. Journ. 84, 1894.  
 Wycoff, S. 1982. In Comets, ed. by L. Wilkening, pp. 3-55. Univ. of Arizona Press.